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Experimental characteristic of a solar parabolic trough collector with indirect steam generation system

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Abstract
The experimental testing shows the construction and testing of three parabolic trough solar collectors (PTSC) experimentally in order to produce moderate-temperature steam. The experimental investigation was carried out on PTSC to testing the thermal performance of the system. The tests were carried out at University of Kerbala / college of engineering with climatic conditions (32.34° N, 44.03° E) for nine days during the month of July and August of 2018. Different parameters of the PTSC system are selected for testing this study such as heat transfer fluid (HTF) type (hydraulic oil, ethylene glycol, and water) and three flow rates of working fluid (1 LPM, 2 LPM, and 3 LPM). A process of steam generation was occurring with a steam temperature of 95.4°C and steam pressure of 2.1 bar. The experiments show that the maximum heat gain and high efficiency can be occurring with using hydraulic oil and the highest value of fluid flow rate. The results show that the maximum useful heat gain is 1.035 kW, 0.879 kW, and 0.734 kW for the case of using hydraulic oil, ethylene glycol based water, and water respectively, with 3 LPM flow rate. The peak experimental efficiencies close to 33.2%, 28.5%, and 22.7% were obtained for PTSC with hydraulic oil, ethylene glycol based water, and water respectively at the highest value of fluid flow rate.

Keywords: Concentrated collector; Solar energy; Parabolic trough collector; Receiver tube; Thermal efficiency.

1. Introduction

Most of the applications of steam generation by solar energy for industrial application and electricity used the method of concentrator solar radiation. Nowadays, parabolic trough solar technology is the best choice for the solar application. The following researches will show the summary for previous work regarding the parabolic trough system.

The first practical experience with Parabolic trough solar collectors (PTSC) goes back to 1870, when a successful engineer, Ericsson, a Swedish immigrant to the United States, designed and built a 3.5m^2 aperture collector which drove a small 373 W engine. Steam was produced directly inside the solar collector (today called Direct Steam Generation or DSG) [1].

Following this more researches are trying to enhance the efficiency of PTSC. Lüpfert et al. [2] studied experimentally thermal properties of receivers of a parabolic trough. In this study different methods to calculate the thermal loss from a receiver tube was presented based on their operating temperature. It was observed that the solar parabolic trough plants with a temperature range of about 390°C were having an energy loss of about 300 W/m of receiver length. Raj et al. [3] performed numerical and experimental analysis on the performance of the absorber tube of a parabolic trough collector system with and without insertion. Water was used as the heat transfer fluid and three different mass flow rates had been used which were 33kg/hr, 63 kg/hr and 85 kg/hr. It was seen that the presence of inserts gave a higher rise in the outlet temperature when compared with the one without insertion which was due to the fact the area of heat transfer was increased with the insertion. It was also observed that the thermal stresses on the tube with insertion were less than that without insertion. A study then done at 2014 by Filho et al. [4] to describes the methodology and the results of an experimental and numerical investigation of the thermal losses of a small scale parabolic trough collector, The numerical simulation when compared to the experimental results for the losses shows the degradation of the vacuum in the annular region of the absorber tube also the collector was tested with solar radiation and the efficiency obtained varied from 0.3 to 0.55. Erdogan et. al [5] presented a designing and analyzing of shell and tube heat exchanger utilized for combine parabolic trough solar collectors (PTSCs) and an organic Rankine cycle (ORC) based geothermal power plant. The results revealed that spacing of baffle is the most prevalent designing parameter, and Dowtherm A or Therminol VP1 as the PTSC side fluid and R245fa or R600 as the ORC side fluid should be chosen. Also, it was found that with increasing the solar irradiation intensity from 450 W/m^2 to 1000 W/m^2 leading to an increase in the minimum heat transfer surface area from 2.644 m^2 to 8.681 m^2. Arun and Sreekumar [6] studying experimentally the parabolic trough solar collector desalination with using a tracking system designed to ease the capture of sunlight with the setting of the sun. The solar intensity range is above 600 W/m^2. The experiment was applied from 11:00 hours to 15:00 hours. The maximum temperature is 103 °C utilizing the glass covered receiver tube and 75°C with utilizing stainless steel receiver tube temperature.

The present work aims to test the PTSC system experimentally to generate steam by using different types of heat transfer fluid (HTF) and with a different value of fluid flow rates 1, 2, and 3 liters per minute (LPM).

2. Description and principles of the PTSC

Parabolic trough solar collector (PTSC) is considered as one of the most mature, successful, and proven solar technologies for electricity generation and steam requirements. The PTSC are typically operated at temperatures range 50-400 ºC [7]. The PTSC system consists of the support structure, parabolic trough, and receiver tube. The parabolic trough-shaped mirror concentrate sun rays onto the receiver tube which is placed in the focal line of the parabola trough as shown in Figure 1.

The receiver tube is typically composed of the glass cover and an absorber tube with a vacuum between these two elements, to reduce heat losses by convection [8]. The receiver usually paints with a selective coating in order to maximize solar radiation absorption. The absorbed solar radiation is conveyed to the heat transfer fluid (HTF) that flows inside the absorber tube. The HTF is provided heat to the thermal system directly by using the fluid or indirectly by transferring heat using a heat exchanger. The HTF leaves the parabolic solar collector is utilized to produce steam that used either in industrial processes or to generate electricity [9].

3. Thermal performance of PTSC

The thermal efficiency of a PTSC can be defined as the ratio of heat gained by the collector, Qu, to the total incident radiation that is incident on the aperture of the collector [10]:

$$\eta_{th} = \frac{Qu}{Aa\, I_b} \tag{1}$$

Where the useful heat gained, Qu, is a function of the outlet and inlet temperature of the heat transfer fluid in the receiver tube as shown below:

$$Qu = \dot{m_f}\, c_p\, (T_{f,o} - T_{f,i}) \tag{2}$$

Thermal efficiency can be found using the following equation [11]:

$$\eta_{th} = \frac{\dot{m_f}\, c_p\, (T_{f,o} - T_{f,i})}{I_b A_a} \tag{3}$$

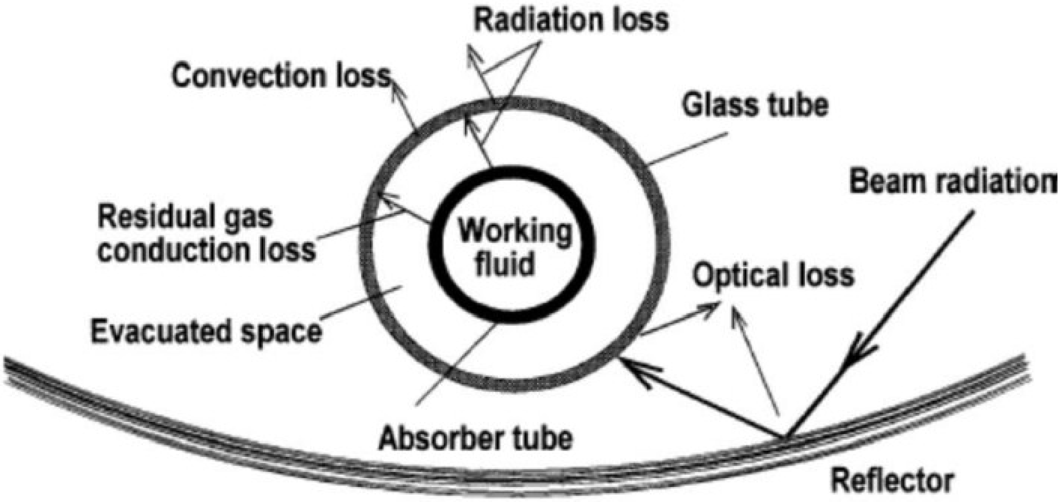

Figure 1. The parabolic trough solar collector system.

4. Experimental rig and test procedure

A PTSC is a concentrating collector, which the reflector surface has a parabolic form as shown in Figure 2. Solar radiation falling on trough then concentrated on the focal line, where a receiver tube was placed. The parabolic collector consists of three troughs, which are arranged in series so that the HTF will gain heat gradually as it flows through the tubes one by one. By circulating the HTF, thermal energy in the HTF will transfer to water by using a coil tank heat exchanger.

The experimental rig is designed, constructed and tested to investigate its ability for steam generation at a moderate temperature. The PTSC system consists of a mechanical structure (support frame), absorber, reflecting parts, evacuated glass tube, heat exchanger, centrifugal pump, auto tracking system and some other accessories. The PTSC specifications are given in Table 1. The glass receiver tube composed of two coaxial borosilicate glass tubes with one open end and another sealed. The experimental setup used for testing the PTSC system shown schematically in Figure 3.

Figure 2. The experimental rig.

Table 1. Specifications of the PTSC.

ITEM	Value/Type
Focal distance (f)	233.1 mm
Glass cover external diameter (D_g)	58 mm
Receiver external diameter (D_r)	47 mm
Concentration ratio (C)	46.8
The effective aperture width (W)	750 mm
Collector length (L)	1800 mm
Parabolic curvature	1220 mm
Total Collector aperture area	3.73 m^2
Reflective material	Aluminum composite panels
Tracking system	One axis auto tracking system
Electrical motor	An electrical motor with moving arm

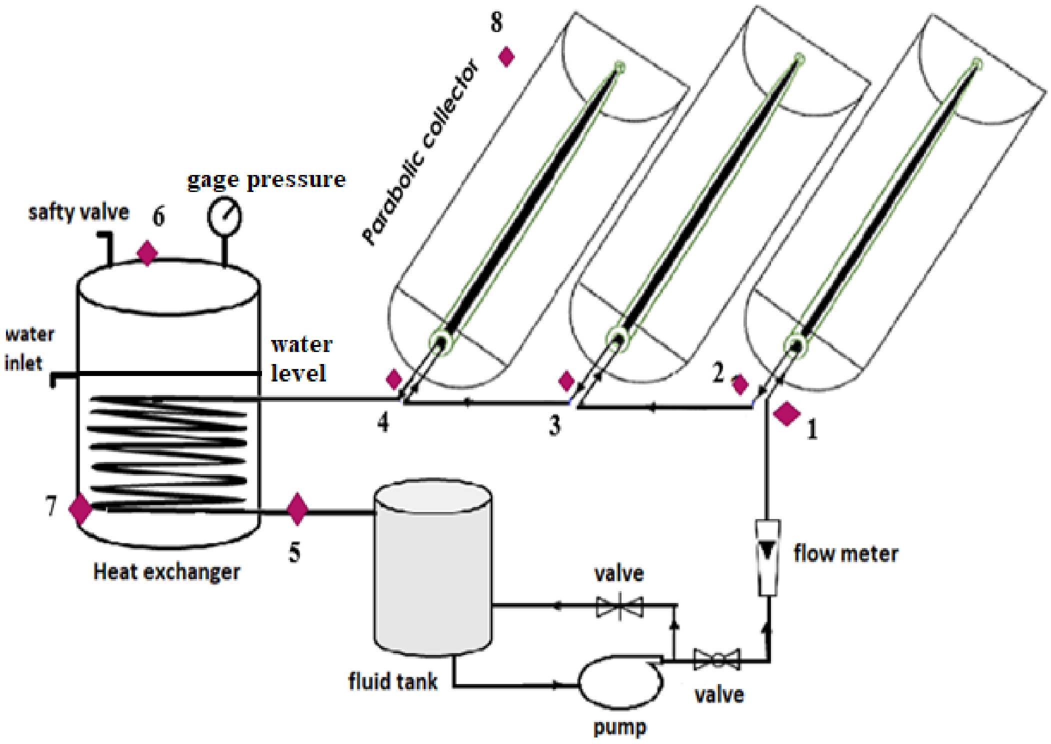

Figure 3. Schematic diagram of the experimental setup.

First, it is very important to clean the reflector from any dirt or dust. Then, pump and tracking motor wires are connected to electricity to running the test. Heat exchanger tank is filled with 30 liters of water (half volume is filled with water only). In the current experiment work, the working fluid is circulated in a closed cycle. The collecting tank is filled with working fluid from the main supply. After this tank had been filled, the outlet from the tank connecting to the pump, then the working fluid is pumped to the inlet of troughs and the trough outlet to the coil inlet then exit from the coil is connecting again to collecting tank. After that, the tracking system of the troughs is turned on and moves the troughs until the sun is directly over the troughs. The flow meter measures the flow rate of the working fluid, which is placed before the troughs inlet and after the pump. The fluid temperatures in their locations (as mentioned in the schematic diagram), ambient temperature, wind speed, the pressure of steam and solar radiation are continuously recorded during the test. After starting the test, working fluid collects heat and its temperature rises, it goes to heat exchanger coil to transferring heat energy to water. This cycle repeats continuously throughout the test period until steam production is achieved. In the current work, three types of working fluid hydraulic oil and ethylene glycol based water and water have been used.

5. Results and discussion

This study presents the experimental investigation to generate steam by using a parabolic trough solar collector PTSC system. The thermal performance of PTSC was calculated from measured data experimentally. The measured data was recorded with different heat transfer fluid (hydraulic oil, ethylene glycol, and water) and with the different flow rate of working fluid (1, 2, and 3 LPM). The tests were conducted at the college of engineering/ University of Kerbala (44.03° Longitude and 32.34° Latitude), through the clear sky days for the months of July and August from 9:00 A.M until 2:30 P.M.

5.1 Heat gain through the collector

The useful heat gained was calculated from the inlet and outlet temperatures through the collector, specific heat, and flow rate of HTF as shown in equation (2). It is noticed from the comparison of different flow rates of HTF as shown in Figures (4, 5 and 6), the useful heat gain is directly proportional to the flow rate of the fluid, in which the heat gain is increased with increasing of fluid flow rate. The maximum heat gain enhancement was 42%, 39.7%, and 24.1% between the fluid flow rate of 1 LPM and 2 LPM for hydraulic oil, ethylene glycol, and water, respectively. While, the maximum heat gain enhancement between the fluid flow rate of 2 LPM and 3 LPM was 24.8%, 16.9%, and 14.2% for hydraulic oil, ethylene glycol, and water, respectively. For example, when the values of flow rate are 1 LPM, 2 LPM, and 3 LPM, the heat gained from the collector varies in the range of 0.144 to 0.583 kW, 0.235 to 0.83 kW, and 0.252 to 1.03 kW, respectively, in case of using hydraulic oil as HTF as shown in Figure 4. And same behaviors were displayed in the Figures 5 and 6 in the cases of using ethylene glycol based water and only water. This phenomenon can be indicated to the known fact that flow rate strongly influences performance through the collector. As the flow rate of the fluid increases, the temperature difference of the fluid through the collector decrease. This lead to lower losses due to the lower temperature around the receiver tube, which is the corresponding rise the heat gain.

Moreover, clearly seen from the Figure 7, the maximum useful heat gain is 1.035 kW, 0.879 kW, and 0.734 kW for the case of using hydraulic oil, ethylene glycol based water, and water respectively. The maximum enhancement in heat gain was 17.7% between hydraulic oil and ethylene glycol. While the enhancement in the heat gain was 19.8% between ethylene glycol and water. The useful heat gain for the hydraulic oil is better than the other two HTF, and the heat gain for ethylene glycol is better than the water and lower than the hydraulic oil with the same flow rates (3 LPM) of the fluid. This is because of the difference in the thermal properties of each type of fluid used and their ability to raise its temperature.

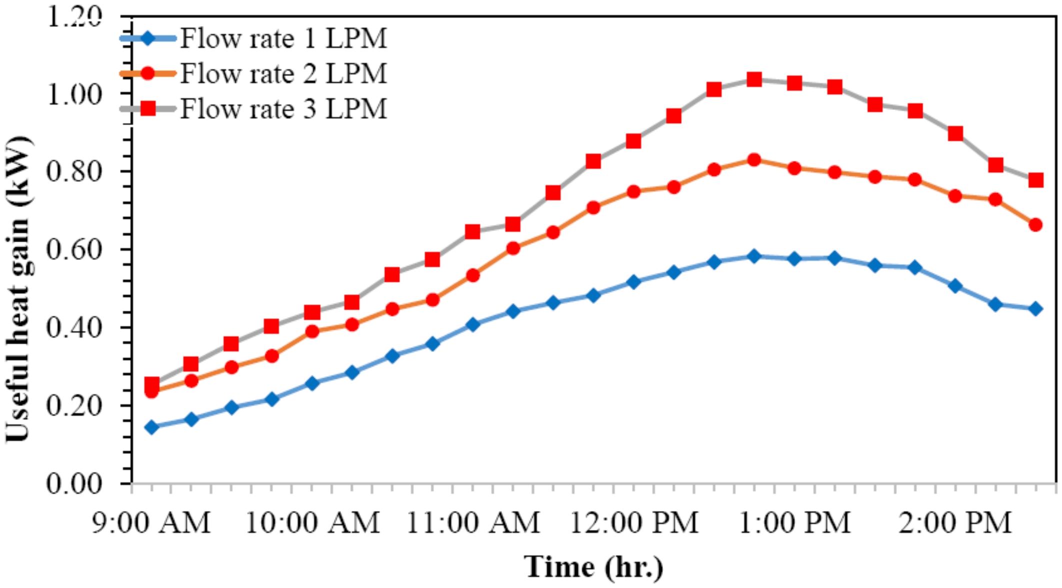

Figure 4. Heat gain with the different flow rate in case of using hydraulic oil.

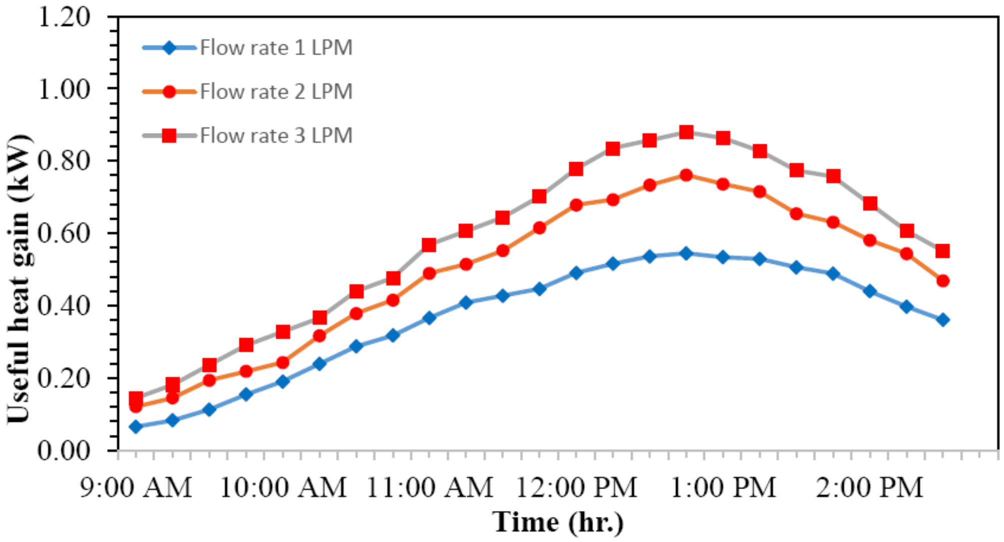

Figure 5. Heat gain with the different flow rate in case of using ethylene glycol.

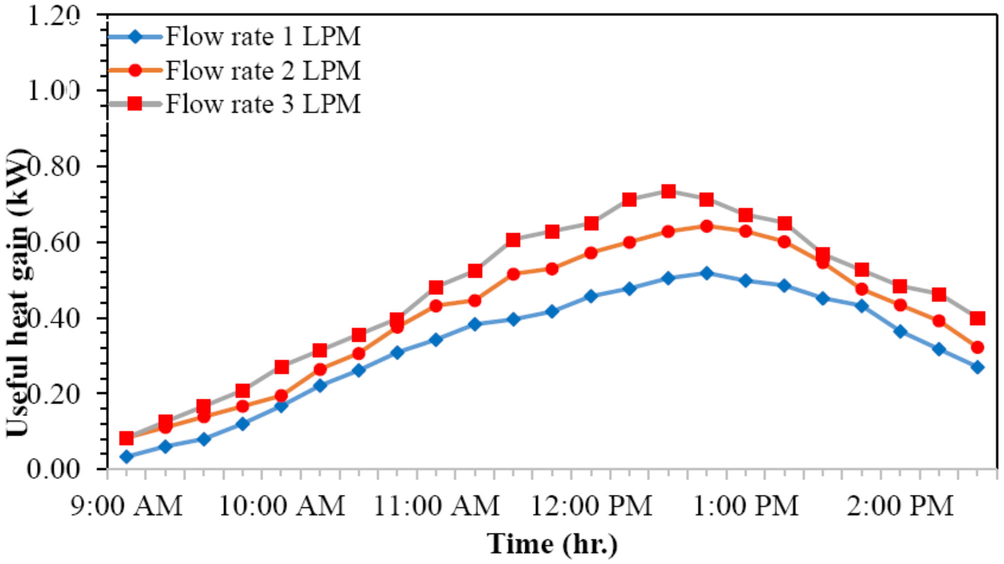

Figure 6. Heat gain with the different flow rate in case of using water.

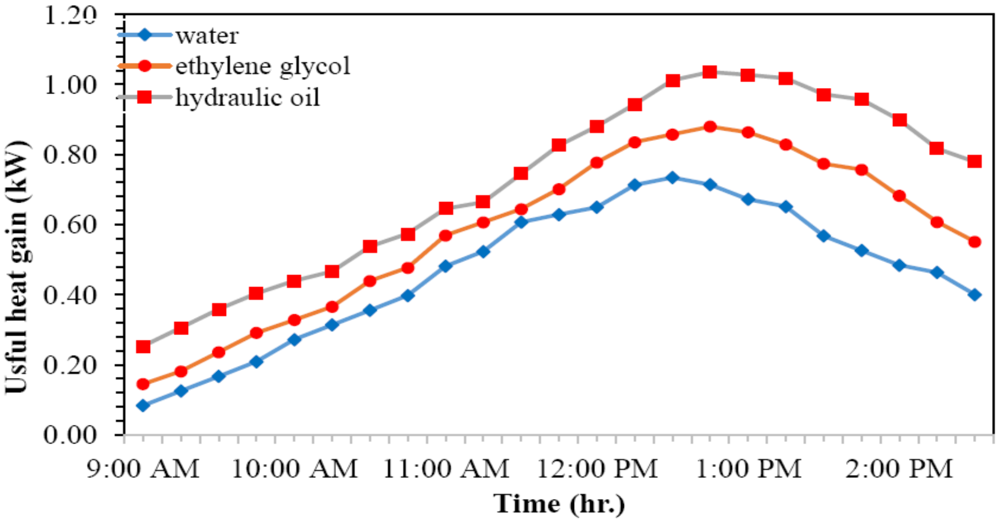

Figure 7. Heat gain for different HTF with time at flow rate 3 LPM.

5.2 Thermal efficiency

Collector thermal instantaneous efficiency is determined from useful heat gain, solar radiation, and aperture area as shown in equation (3). It can be deduced from the Figures 8, 9 and 10, the thermal efficiency has a directly proportional relation with the fluid flow rate through the collector. As the flow rate increase, the thermal efficiency increase. For example, when the values of flow rates were 1 LPM, 2 LPM, and 3 LPM, the instantaneous thermal efficiency varies in a range of (6.4 % to 19.08 %), (10.2 % to 26.7 %), and (11.1 % to 34.06 %), respectively, for hydraulic oil as a HTF. Similar behavior was shown for the other cases. This is due to the highest value of heat gained by the collector is occur when the flow rate at maximum value, which causes the reduction of heat losses as mentioned previously. Thus, increasing in the heat gain and thermal efficiency through the collector. Generally, it was observed that the patterns of variation of thermal efficiency during the day are similar to that of heat gained, due to the thermal efficiency is depended on the solar radiation and the heat gain. Figure 11 shows the comparison between the thermal efficiency of different HTF (hydraulic oil, ethylene glycol based water, and water) at flow rate 3 LPM. The maximum difference in thermal efficiency was 16.4% between hydraulic oil and ethylene glycol. While the difference between thermal efficiency reaches about 21.4% between ethylene glycol and water. It is clear that hydraulic oil gives better thermal efficiency than other HTF, and thermal efficiency of ethylene glycol is higher than water but lower than hydraulic oil with the same flow rate. This is due to the different heat capacity of HTF.

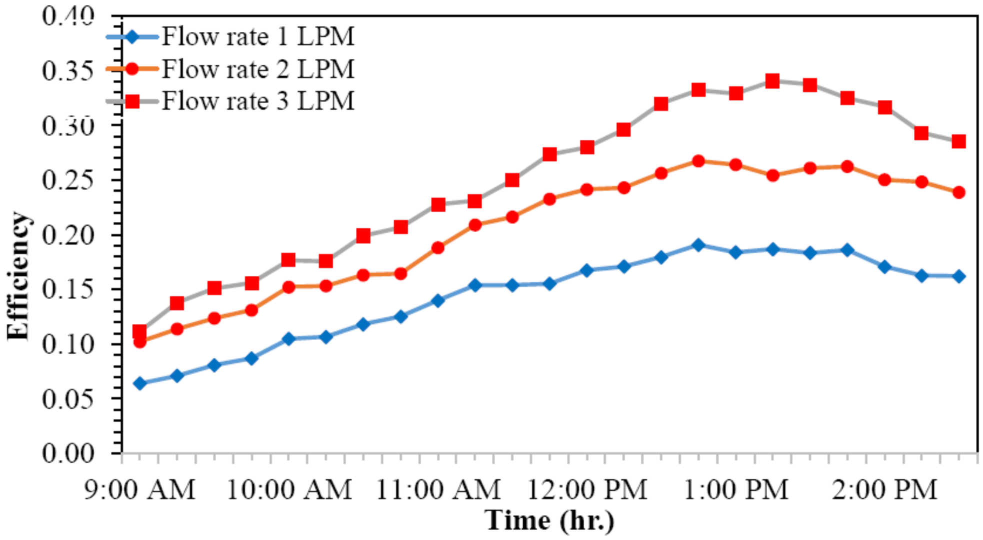

Figure 8. Thermal efficiency for different flow rate with time for hydraulic oil.

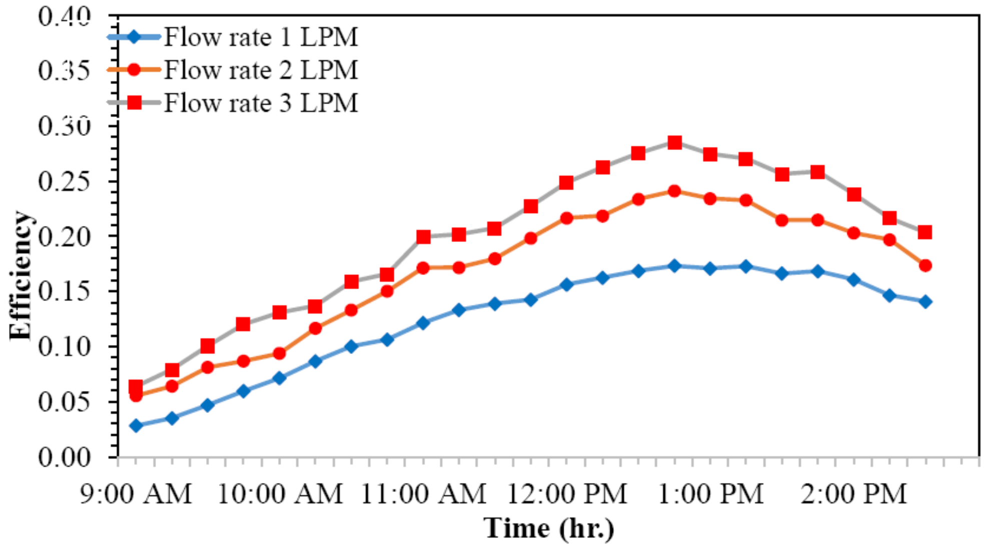

Figure 9. Thermal efficiency for different flow rate with time for ethylene glycol.

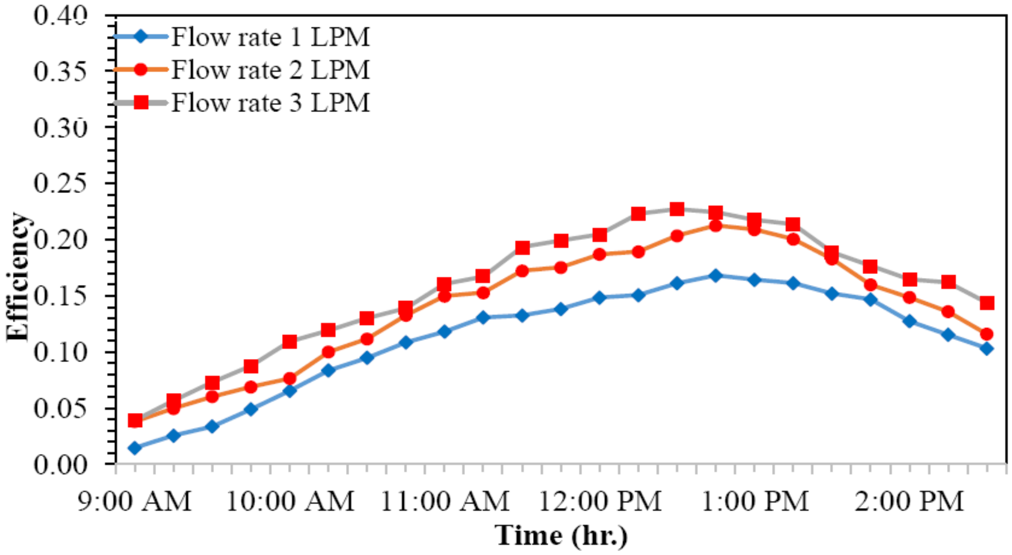

Figure 10. Thermal efficiency for different flow rate with time for water.

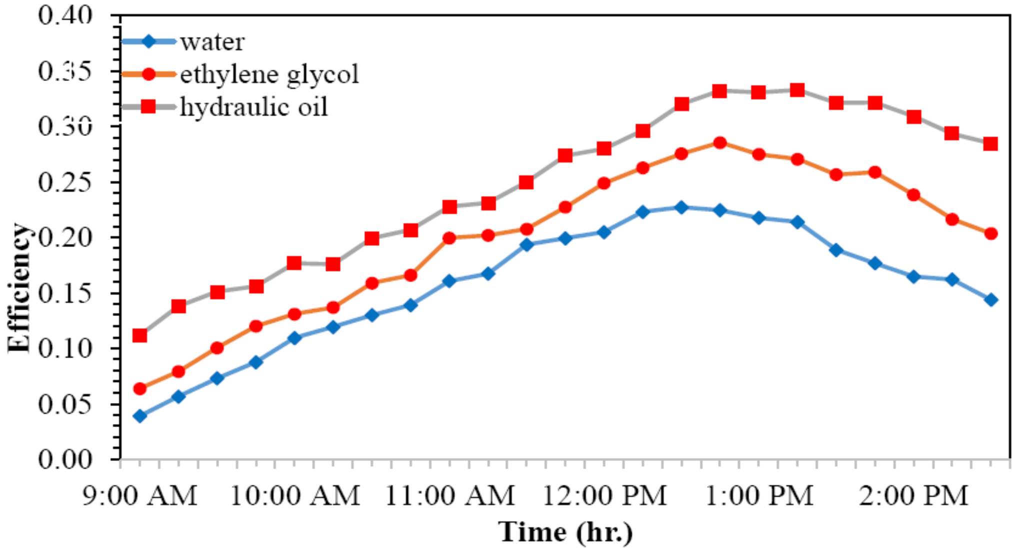

Figure 11. Thermal efficiency for different HTF with time at flow rate 3 LPM.

5.3 Steam generation

Moreover, when the temperature of the water inside the tank of the heat exchanger increase, the steam pressure inside the tank increase also. The pressure gauge is fixed on the tank and it measures the pressure of steam inside the tank during the experiments days. The heat exchanger tank, which is filled with water and leaves part of its volume empty, allows steam to be generated inside the tank. Water (inside the heat exchanger) gains thermal energy from the circulated heat transfer fluids and its temperature starts to increasing (reach to 95.4 ^{o}C in case of using hydraulic oil). The pressure increases continuously until it reaches about 1.9 - 2.1 bar. Figure 12 shows water temperature and steam pressure with time in case of using hydraulic oil and flow rate 3 LPM. The steam generation process has been achieved at moderate temperatures 95.4 ^{o}C and steam pressure about 2.1 bar.

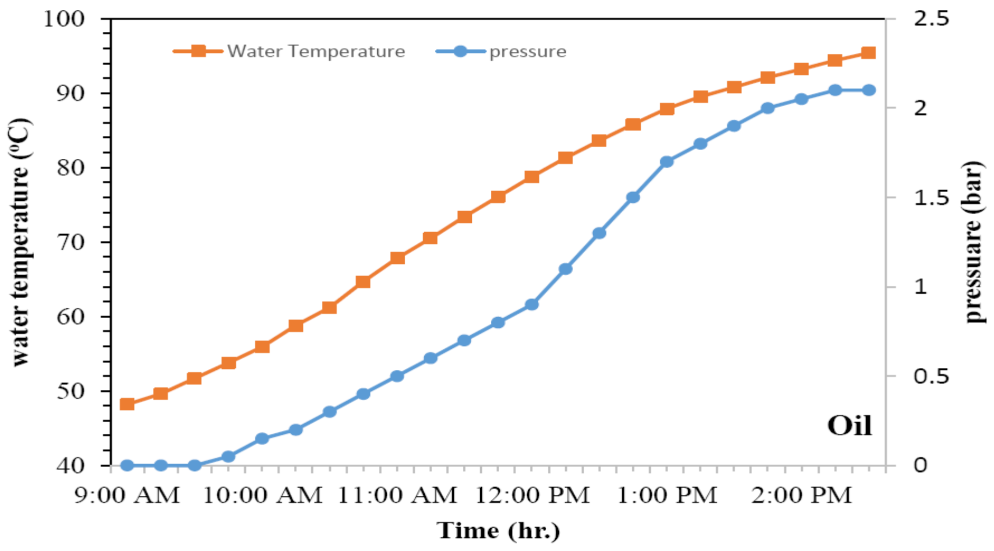

Figure 12. Water temperature and steam pressure with time for hydraulic oil 3 LPM flow rate.

6. Conclusions

An experimental investigation has been carried out for analyzing the thermal performance of PTSC experimentally so as to generate steam at medium temperature. In this study, the experimental tests carried out with three types of heat transfer fluids (hydraulic oil, ethylene glycol, and water) and three values of fluid flow rate (1, 2, and 3 LPM). The performance of the PTSC system depends on the measured parameters such as ambient temperature, the inlet temperature of HTF, the outlet temperature of HTF, and solar intensity. A peak experimental efficiencies close to (33.2%, 28.5%, and 22.7%) were obtained for parabolic trough collectors with hydraulic oil, ethylene glycol based water, and water respectively at the highest value of flow rate.

Nomenclature

A_a	Collector Aperture area	$T_{f,i}$	Inlet Fluid Temperature to the Collector
C_p	Specific Heat	$T_{f,o}$	Outlet Fluid Temperature from the Collector
I_b	Beam Radiation	η_{th}	Thermal efficiency
$\dot{m}$	Mass flow rate	HTF	Heat transfer fluid
Q_u	Useful Heat Gain by the collector	PTSC	Parabolic trough solar collector

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